Radiation Effects Testing at the 88-Inch Cyclotron[1]

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Abstract

The 88-Inch Cyclotron at the Lawrence Berkeley National Laboratory provides radiation effects test facilities for both heavy ions and protons. The wide range of ions available, and the use of "cocktail" beams, allowing users to switch back and forth between several heavy ion beams without a retune of the accelerator, makes this facility a very versatile and economical choice for radiation effects testing.

Le 88-Inch Cyclotron, situé à Lawrence Berkeley National Laboratory délivrant des faisceaux d'ions légers et des ions lourds (de protons à ^{238}U). Cette diversité allait permettre d'utiliser les faisceaux d'ions composés – "cocktail", donc le expérimentateur peut choisir entre les différents ions sans changer la réglage du cyclotron. Cette possibilité fait le 88-Inch Cyclotron un centre de recherche des effets de la radiation tres pratique et économique.

I. INTRODUCTION

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory is run by the U.S. Department of Energy for basic research in low energy nuclear physics and chemistry. Up to 1000 hours/year is available for applied work on a recharge basis. Much of that time is used for radiation effects testing (RET) and calibration of detectors for upcoming space flights. Other applications include radiation hardness measurements of bulk material and some ion implantation.

II. THE CYCLOTRON AND ITS BEAMS

The central component of the 88-Inch facility is a sector-focussed, variable-energy cyclotron fed by two Electron Cyclotron Resonance (ECR) high charge-state ion sources. Light ions – p, d, ^{3}He and ^{4}He – are produced up to total energies of 55, 65, 135 and 130 MeV, respectively. Light heavy ions can be produced at energies up to 32 MeV/nucleon. As the mass increases, the maximum energy per nucleon decreases. A particle nanoamp of ^{209}Bi is available up to an energy of 4.5 MeV/nucleon. Recently, trace amounts of ^{238}U (≈10 counts/sec) were obtained at 8.4 MeV/nucleon. Figure 1 shows all elements which have been accelerated through the Cyclotron. Other beams can be developed as needed.

The combination of cyclotron and ECR source provides the unique ability to run "cocktails" of ions. [1] A cocktail is a mixture of ions of near-identical charge-to-mass (q/m) ratio. The ions are tuned out of the source together and the cyclotron acts as a mass analyzer to separate them, allowing one to switch from one ion to another with small adjustments of the accelerator RF. This means that the ion and therefore the linear energy transfer (LET) delivered to the component can be changed in approximately one minute. Intensity variations between the components of the cocktail are compensated for with a series of attenuator grids at the ion source which allow adjustments over nine orders of magnitude.

The four cocktail combinations most commonly in use at the 88-Inch Cyclotron are summarized in Table 1. Figure 2 plots the LET versus range for each element of the four cocktails. Certain elements of each cocktail are standard, and others can be added as needed. For example, the 4.5 MeV/nucleon heavy ion cocktail is the cocktail most commonly used for RET work and, in standard form, gives a range of LET from 2.9 to 61.8 MeV/mg/cm^2. If a lower LET is needed, boron can be added at 1.5 MeV/mg/cm^2. If a higher LET is needed, bismuth (LET = 98.3 MeV/mg/cm^2) is run. The bismuth beam comes from the upgraded Advanced-ECR source (AECR-U) so the switchover takes about 30 minutes. Cocktails at intermediate energies are available.

The versatility of the ECR/cyclotron combination allows other tricks, such as quickly changing the beam energy by changing the charge state of the ions. [2] This results in expanded versions of the heavy ion cocktails which are not included in Table 1. For example, the standard 10 MeV/nucleon cocktail contains seven elements. With expanded tuning, N, O, Si and S are available, as well as a wider range of energies for the standard components. For example, by varying the charge state of the ^{136}Xe from +34 to +42, the energy changes from 1014 to 1544 MeV and the LET from 52.0-57.4 MeV/mg/cm^2 over ≈0.7 MeV/mg/cm^2 steps.

Protons are available to a maximum energy of 55 MeV and currents from a few hundred ions/sec up to 20µA. Depending on the size of the area to be irradiated and the dosimetry method employed, total doses of 10^{15} ions/cm^2 can easily be obtained and higher doses are feasible. Protons are available at energies as low as 1 MeV; special dosimetry is required below ≈6 MeV.

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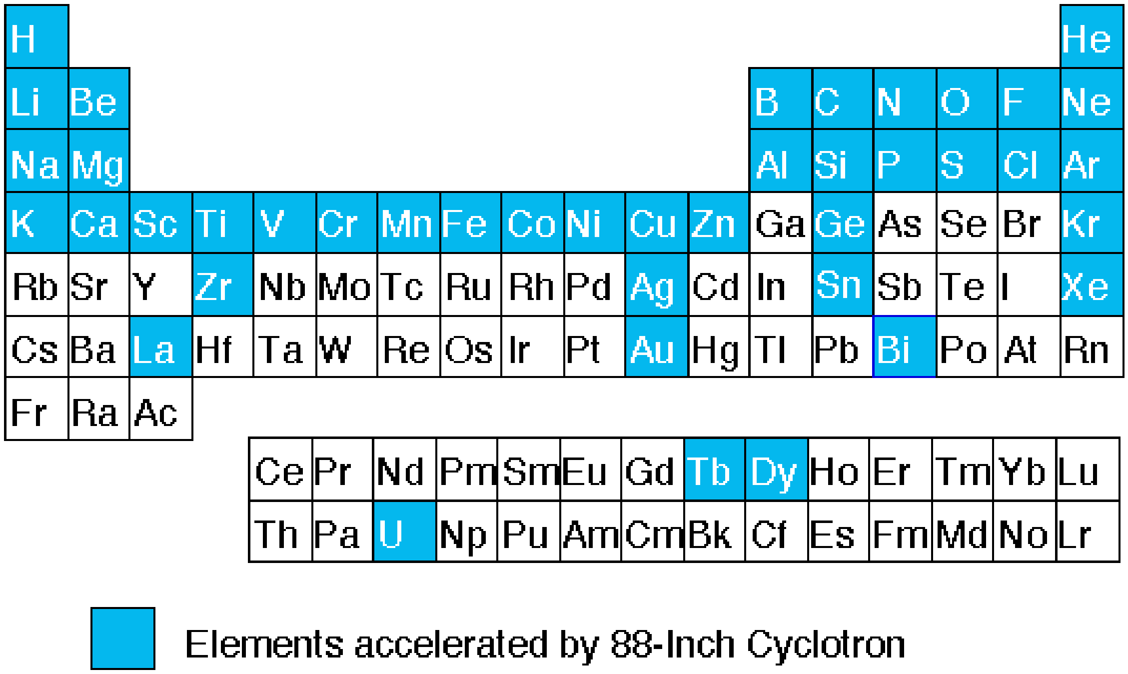

Figure 1. Elements accelerated by the 88-Inch Cyclotron

III. The Radiation Effects Test Facilities

The primary test chamber for heavy ion RET studies is located in Cave 4b of the facility, where Aerospace Corporation and 88-Inch Cyclotron Operations have collaborated to install an end station for RET and detector calibrations. The vacuum chamber is large, in order to accommodate large circuit boards or whole systems. It has been designed to pump down in only a few minutes. A special table allows remote movement of the circuit board in any direction or angle, and a laser and CCD camera system enables alignment of parts remotely while under vacuum. The vacuum controls are presently being upgraded to allow remote operation as well. A diagnostic box upstream of the main vacuum chamber contains a scintillator system for dosimetry, a silicon detector for energy measurements and various collimators and shutters. Computer software developed by Aerospace Corporation controls the dosimetry, table motion and other elements of operation.

Flanges are available with various kinds of connectors to interface to the outside of the vacuum system. BNC, SHV and ribbon cables run approximately 10 meters to a trailer located directly above the cave. The trailer contains electronics and computers for dosimetry plus room to set up user electronics and diagnostic equipment.

The Irradiation Station in Cave 3, developed for biology studies, is used extensively for proton and light ion cocktail irradiations. Experiments are set up in air on an optical bench. A uniform beam (to approximately 5%) can be delivered with a diameter up to 10 cm. Uniformity and dose are measured using an ionization chamber. A Macintosh/Labview‡ system has been developed to display dose and flux and control the beam for runs at the Cave 3 Irradiation Station. Other available equipment include an X-ray film developer for confirming beam uniformity, a Faraday cup as alternative dosimetry or for calibration of the ionization chamber, and various silicon detectors for measuring beam energy.

For some applications a larger beam is required. In these cases the ionization chamber can be set up on a beamline which has been modified to use beams up to 15 cm in diameter. This beamline also has a vacuum chamber which is available for heavy ion work.

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References

[1] M.A. McMahan, et. al. “Using a Cyclotron plus ECR Source for Detector Evaluation and Calibration”, Nucl. Instr. Meth. **A253**, 1 (1986).

[2] D.J Clark and G.J. Wozniak, “Fast Energy Changes with a Cyclotron”, Nucl. Inst. Meth., **A295**, 34 (1990).

Table 1. Summary of cocktail beams

Cocktail	Standard Ions	Other Ions[a]	LET (MeV/mg/cm^2)	Range in Si
4.5 MeV/nucleon (HI)	^{15}N, ^{20}Ne, ^{40}Ar, ^{65}Cu, ^{86}Kr, ^{136}Xe	HeH[b], ^{10}B, ^{59}Co, ^{78}Kr, ^{209}Bi	2.9-61.8 (standard) 0.26-98.3 (all)	43-69 μ (standard) 40-180 μ (all)
10 MeV/nucleon (HI)	^{10}B, ^{20}Ne, ^{27}Al, ^{40}Ar, ^{63}Cu, ^{86}Kr, ^{136}Xe	None	0.84-52.7	115-330 μ
19 MeV/nucleon (LI)	H_2[b], ^{4}He, ^{14}N, ^{16}O, ^{20}Ne, ^{36}Ar	^{2}H, ^{28}Si, ^{32}S, ^{40}Ca	0.022-6.58 (standard) 0.022-8.01 (all)	0.29-2.15 mm (standard) 0.27-4.29 (all)
32.5 MeV/nucleon (LI)	H_2[b], ^{4}He, ^{14}N, ^{16}O, ^{20}Ne, ^{36}Ar	^{2}H, ^{28}Si, ^{32}S, ^{40}Ca	0.014-4.46 (standard) 0.014-5.46 (all)	0.69-5.56 (standard) 0.63-11.1 (all)

[a]These ions require special arrangements and advance notice.

[b] LETs and Ranges for molecular ions are calculated for separate components after breakup in target or scattering foil.

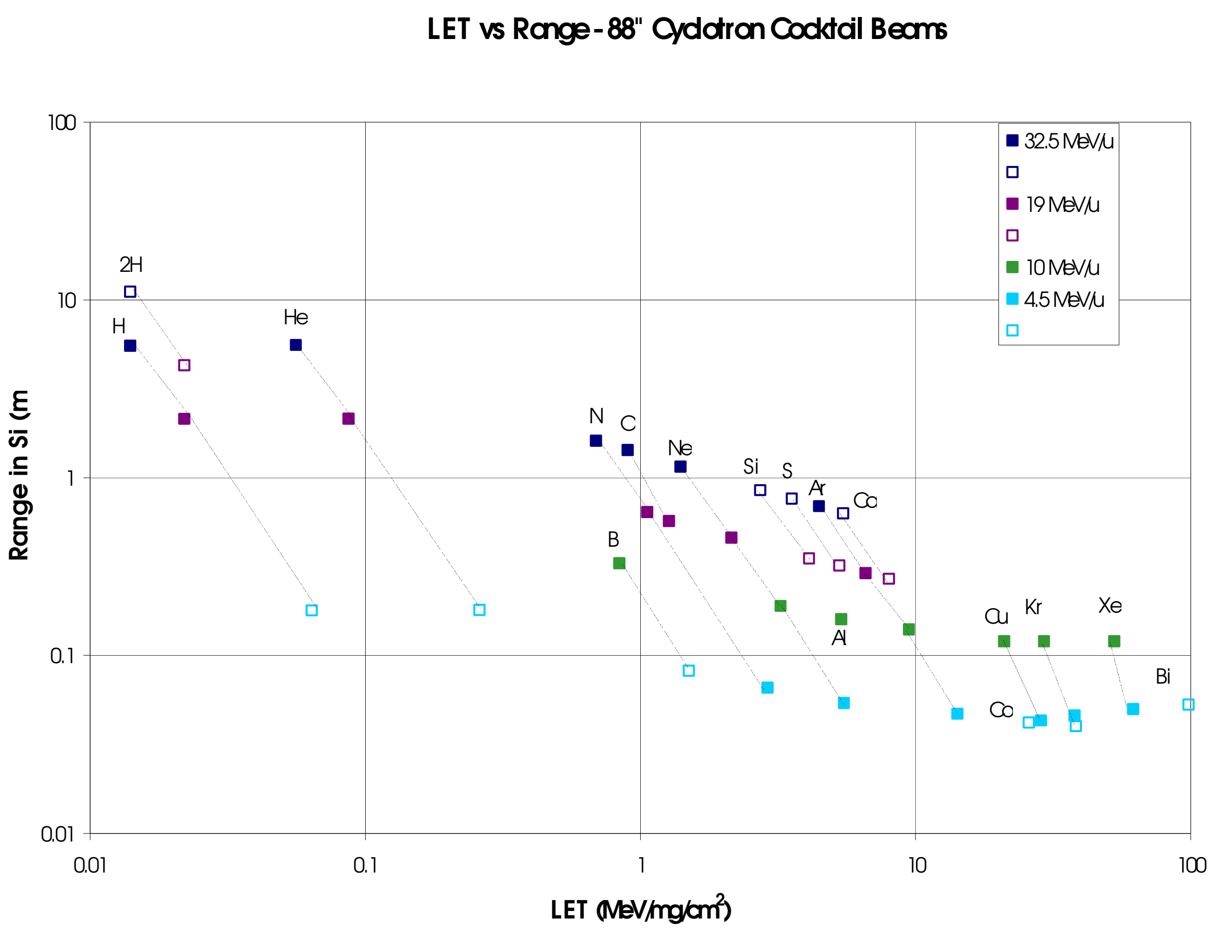

Figure 2. LET versus Range for the four standard cocktail beams listed in Table 2. Standard components are shown with solid squares and additional components with open squares.